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# Tip Clearance Flows in Turbine Cascades

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## Abstract

This article describes the effects of some factors on the tip clearance flow in axial linear turbine cascades. The measurements of the total pressure loss coefficient are made at the cascade outlets by using a five-hole probe at exit Mach numbers of 0.10, 0.14 and 0.19. At each exit Mach number, experiments are performed at the tip clearance heights of 1.0%, 1.5%, 2.0%, 2.5% and 3.0% of the blade height. The effects of the non-uniform tip clearance height of each blade in the pitchwise direction are also studied. The results show that at a given tip clearance height, generally, total pressure loss rises with exit Mach numbers proportionally. At a fixed exit Mach number, the total pressure loss augments nearly proportionally as the tip clearance height increases. The increased tip clearance heights in the tip regions of two adjacent blades are to be blame for the larger clearance loss of the center blade. Compared to the effects of the tip clearance height, the effects of the exit Mach number and the pitchwise variation of the tip clearance height on the cascade total pressure loss are so less significant to be omitted.

**Keywords:** tip clearance flow; turbine cascade; tip clearance height; total pressure loss coefficient

## 1 Introduction

The tip leakage flow is one of the most common features of great significance of the flow in turbomachine rotors. The pressure difference across the blade causes the leakage flow from the pressure surface to the suction surface of the blade. On leaving the gap on the suction surface side, the leakage flow interacts with the passage flow to form a vortex around the suction surface corner of the blade tip, dominating the aero-thermodynamic behavior of the flow in the tip region, and accounts for one third of overall loss in the turbine stage. However, both reducing loss and increasing efficiency always constitute one of important duties to the turbine designers, so the research on the structure of tip clearance flow and the mechanism of losses due to it has been

attracting closest attention from specialists working on compressors and turbines<sup>[1–19]</sup>.

A detailed review of literature on the problem of the tip clearance flow in axial turbines was made by Sjolander<sup>[1]</sup>. A large amount of work on the tip clearance flow was done by way of theoretical analysis<sup>[2–3]</sup>, numerical simulation<sup>[4–6]</sup>, and experimental investigation<sup>[7–19]</sup>. There were presented two different tip clearance loss models<sup>[2–3]</sup>. Tallman, et al. computed the tip clearance flow in a linear turbine cascade to clarify the details of flow physics taking into account the effects of tip clearance height and the relative motion of outer casing<sup>[4–5]</sup>. Ref.[6] simulated the effects of Reynolds number on tip clearance flow in a certain turbine rotor under a real working condition characterized by high temperature, high pressure ratio, and high rotation. A lot of experimental work was carried out on cascades and rotors. On turbines, measurements of the tip clear-

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ance flow were made on the linear turbine cascades with three different tip clearance heights from 2.0% to 3.2% of the blade chord<sup>[7-8]</sup>. The velocity, the flow direction, and the total pressure within the gap were measured in detail. The results indicated that, with a simple model, the mass flow rate distribution, the magnitude and the direction of the velocity vectors within the gap could be predicted accurately<sup>[7]</sup>. In Ref.[8], a measurement was made on 40% of an axial chord downstream of the blade trailing edges which showed the additional loss due to tip leakage equal to the sum of the measured loss at the exit plane of the tip gap and the amount of the secondary kinetic energy at it. Ref.[9] experimentally studied the effects of three different tip clearance heights and two Reynolds numbers on the tip clearance loss of the flat tip platform. Matsunuma investigated the effects of Reynolds number and free-stream turbulence on turbine tip clearance flow in an annular turbine wind tunnel<sup>[10]</sup>. Refs.[11-12] performed an experimental investigation on the tip clearance flow in a low-speed single-stage axial turbine rotor by measuring the distribution and the development of the pressure, the loss, the velocity, and the turbulence fields. In compressors, Kang carried out a detailed measurement on the tip clearance flow field in a linear compressor cascade<sup>[13-14]</sup>. Tang<sup>[15]</sup> conducted a thorough study on the structure of tip-gap turbulent flow structure in a low-speed linear compressor cascade wind tunnel that includes a moving belt system to simulate the relative motion between the tip and the casing. On the base of Ref.[15], the interaction between the rotor blade tip leakage vortex and the inflow disturbances was measured by Nanyaporn<sup>[16]</sup>. Moreover, by using stereoscopic particle image velocimetry (SPIV), Ref.[17] analyzed the evolution of tip clearance vortex and Ref.[18] measured unsteady flow field in the tip region in cross flow sections under near stall conditions in a low-speed compressor. The formation and interaction of small-scale vortices and mainstream characterize the flow in the compressor rotor. The effects of Coriolis force and centrifugal force on the stability of tip clearance vortex were analyzed theo-

retically, on the supposition of incompressible, inviscid and quasi-cylindrical swirling flow<sup>[17]</sup>. The three-dimensional turbulent flow of the tip leakage vortex in an axial compressor rotor was studied by a 3-component laser doppler velocimetry<sup>[19]</sup>.

Although complicity of the tip clearance flow is not a new problem, the data available in existing literature could not fully explore and compare the effects of tip clearance height and exit Mach number upon the clearance flow field. In addition, the changes in tip clearances during engine operation, which are caused by erosion and/or scrape between the tip platform and the outer casing and by manufacturing tolerances leads to uneven pitchwise variation of tip clearance height. This would induce blade-to-blade non-periodicity. Nevertheless, up till now there was little done on the effects of non-uniform tip clearance heights. Therefore, this work is devoted to measurement of the flow field at the cascade outlet by using a five-hole probe at exit Mach numbers of 0.10, 0.14 and 0.19. For each exit Mach number, experiments are performed with the tip clearance heights of 1.0%, 1.5%, 2.0%, 2.5% and 3.0% of the blade height. The effects of the pitch-wise non-uniform tip clearance height of each blade are also studied.

## 2 Experimental Facility and Instrumentation

The experiments were conducted on a low-speed turbine cascade wind tunnel at the Northwestern Polytechnical University (NWPU). Powered by a 18 kW motor with a fan, the wind tunnel comprises a diffuser, a settling chamber, a series of flow conditioning screens, a contraction and a test section (see Fig.1).

In the test section, there is a cascade of nine blades installed between two parallel end-plates which are aligned horizontally. Perpendicular to the flow direction, the inlet section is of a rectangular form, 300 mm × 90 mm in dimension. The three middle blades with flat tips are cantilevered from the upper wall of the cascade and fixed by six screws. The tip clearance height can be adjusted by

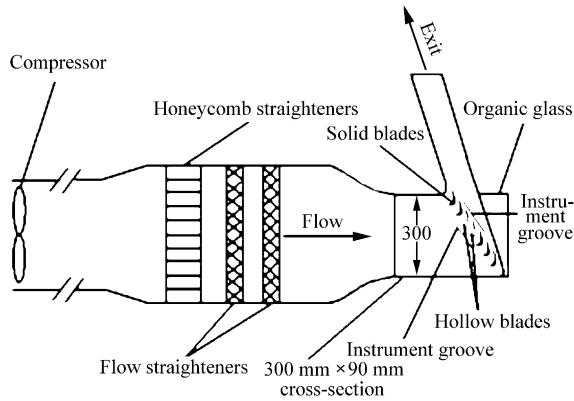


Fig.1 Low-speed turbine cascade wind tunnel of NWPU.

a precision copper washer embedded between the upper wall and the blade with an allowance of  $\pm 0.05$  mm for the five tip clearance heights. There is none of tip clearance in other six blades. In the present study the tip clearance heights were chosen to be 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% of blade height. The blade profile parameters specified by Jouini<sup>[20]</sup> were adopted and the turbine cascade geometric parameters are listed in Table 1.

Table 1 Turbine cascade information

Span length/mm	90
Chord length $C$ /mm	58
Axial chord length/mm	53.6
Pitch length/mm	43
Inlet metal angle/(°)	46.0
Exit metal angle/(°)	59.0

Specially designed for this cascade tunnel, a traverse system consists of a three-axis movement system. Movements on each axis are controlled by individual stepping motors equipped with PC. Traverse measurements in the 40% chord downstream of the cascade exit plane by mean of a five-hole probe are made at five different tip clearance heights. In the traverse plane 59 stations are arranged, each having 12 sub-stations taken from near-endwall to midspan.

The  $\varnothing 2.6$  mm five-hole probe was disposed in the three-axis coordinate movement system. Fixed to the upper wall of the cascade, the probe was inserted into the flow field and had been calibrated in a jet. The accuracy of the measurements of total pressure and velocity was within 0.01% of the val-

ues recorded at the inlet midspan where all the reference parameters were taken. The uncertainty of the measured flow direction was less than  $1^\circ$ .

This paper considers three different exit Mach numbers: 0.10, 0.14, and 0.19. The corresponding Reynolds numbers, based on blade chord and outlet velocity, were approximately  $1.23 \times 10^5$ ,  $1.91 \times 10^5$ , and  $2.51 \times 10^5$ . The free stream turbulence intensity was less than 1%.

### 3 Results and Discussion

#### 3.1 Effect of the tip clearance height

The effects of the tip clearance height on the tip clearance flow were investigated by measuring the total pressure loss coefficient distribution at the 40% chord downstream of the cascade exit plane. Total pressure loss is defined in terms of a coefficient as

$$\xi = \frac{P_{\text{inlet}} - P_{\text{local}}}{Q_m}, \quad Q_m = \frac{1}{2} \rho U_m^2$$

where  $P_{\text{inlet}}$  represents the inlet total pressure,  $P_{\text{local}}$  the local total pressure,  $\rho$  density and  $U_m$  the inlet velocity at midspan.

In order to compare with the no-tip case, five cases—1.0% $H$ , 1.5% $H$ , 2.0% $H$ , 2.5% $H$ , and 3.0% $H$  were examined, where  $H$  denotes the blade height. Fig.2 shows the distribution of total pressure loss coefficients in the no-tip case at  $Ma = 0.19$ . The abscissa is the axial chord position and  $y$  axis the relative height which takes account of the blade height  $H$ . Fig.3 shows the distribution of total pressure loss coefficient with 1.0% $H$  case at  $Ma = 0.19$  and Fig.4 in 2.5% $H$  case at  $Ma = 0.19$ . The region of the tip clearance flow and the entrainment of fluid around it are viewed as the region where the coefficients of high total pressure are high. This region in association with the tip clearance vortex is primarily ascribed to the swirling of the vortex. From Fig.2, it can be seen the passage vortex. By comparing Fig.2 with Fig.3, it is clear that tip clearance vortex does exist. Ref.[8] also made reference to the passage vortex and the tip clearance vortex. The high loss region associated with the tip

leakage flow in  $2.5\%H$  case seems larger in size and higher in quantity than that in the  $1.0\%H$  case. As the tip clearance height increases, the tip clearance flow strengthens, and the tip clearance vortex also becomes larger and stronger.

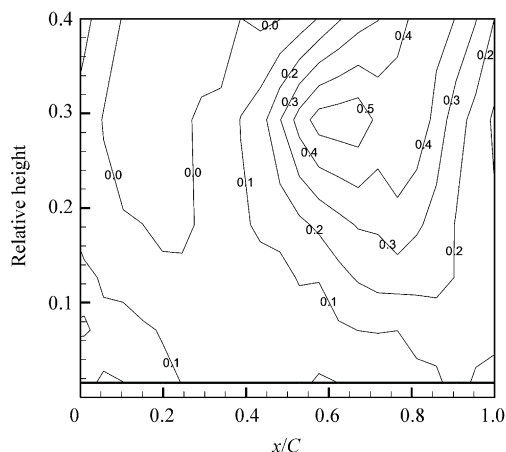


Fig.2 Total pressure loss coefficient contours with no tip at  $Ma = 0.19$ .

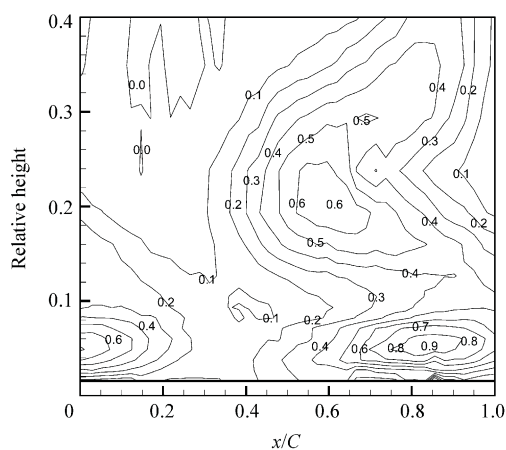


Fig.3 Total pressure loss coefficient contours with  $1.0\%H$  case at  $Ma = 0.19$ .

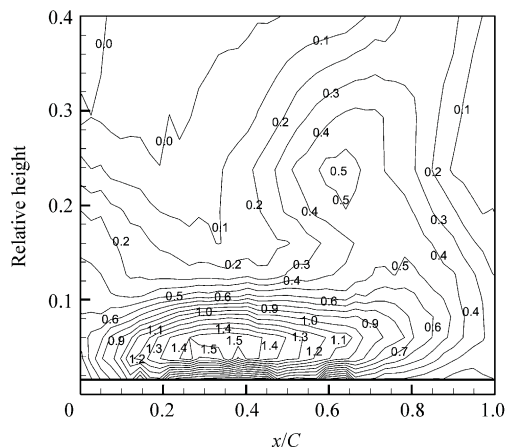


Fig.4 Total pressure loss coefficient contours with  $2.5\%H$  case at  $Ma = 0.19$ .

### 3.2 Effects of the exit Mach numbers

For the purpose of studying the effects of the exit Mach number on the tip leakage flow, three different Mach numbers, 0.10, 0.14, and 0.19, were chosen. Fig.5 shows the distribution of total pressure loss coefficients in  $2.0\%H$  case at  $Ma = 0.10$ . Fig.6 shows the same in  $2.0\%H$  at  $Ma = 0.19$ . The results illustrate that the increase of exit Mach number results in the slightly enlarged loss region due to the tip leakage flow, and the mass averaged total pressure loss increases insignificantly, which can be seen from Fig.7.

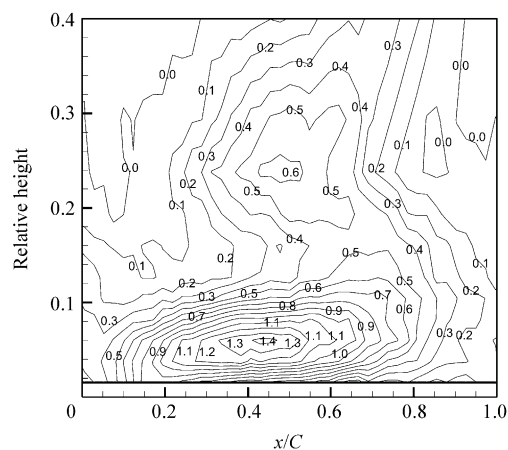


Fig.5 Total pressure loss coefficient contours with  $2.0\%H$  case at  $Ma = 0.10$ .

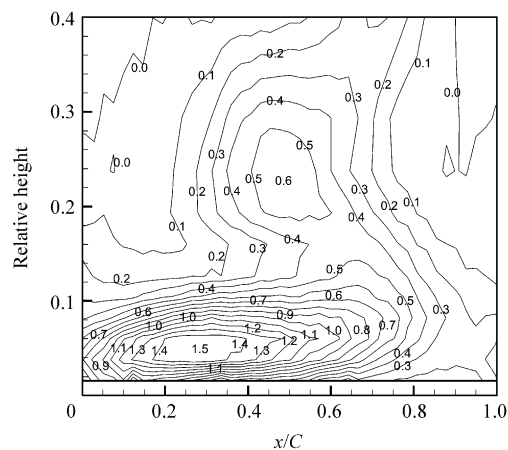


Fig.6 Total pressure loss coefficient contours with  $2.0\%H$  case at  $Ma = 0.19$ .

### 3.3 Effects of non-uniform tip clearance height

The tip clearance height would never be uniform because the tip clearance always changes during working because of erosion of blades and/or

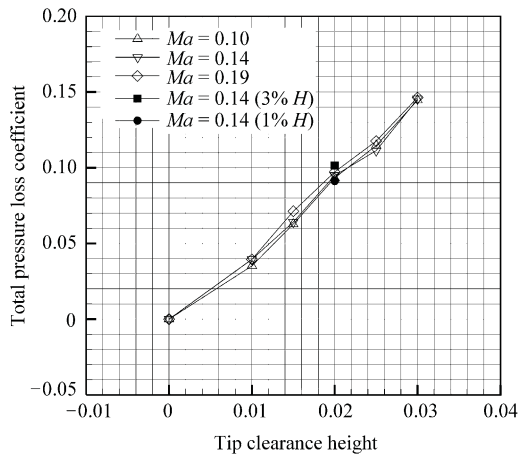


Fig.7 Mass averaged tip clearance loss vs tip clearance height and exit Mach number.

scrape between tip platform and outer casing and manufacturing tolerances. Non-uniform tip clearance heights would induce blade-to-blade non-periodicity. In order to examine the effects of blade-to-blade non-periodicity on tip clearance loss, the tip clearance height of the middle central blade is made different from other two adjacent blades. There are two cases in tests: (1) the tip clearance height of the central blade is set to be 2% $H$  and those of other blades 1% $H$ , Fig.8 shows the distribution of total pressure loss coefficient; (2) the heights of other two blades are set to be 3% $H$  while that of the central blade remains unchanged. Fig.9 shows the distribution of total pressure loss coefficient. To compare the effects of non-uniform tip clearance height, the total pressure loss coefficients of three central blades with uniform tip clearance height of 2% $H$  were measured. Fig.10 presents the measured data. In all cases, measurements are conducted to the same tolerance. From these results, it can be seen that the tip clearance heights of two adjacent blades have an influence on the distribution of the total pressure loss coefficients. As the increase of tip clearance heights of adjacent blades broadens the pressure difference between the pressure side and the suction side in the central passage, the tip clearance flow across the tip gap becomes stronger and the tip clearance vortex in the central blade more serious.

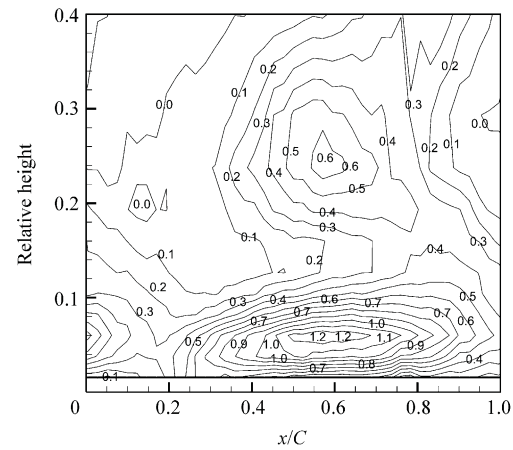


Fig.8 Total pressure loss coefficient contours with central blade 2.0% $H$  case and adjacent blade 1.0% $H$  case at  $Ma = 0.14$ .

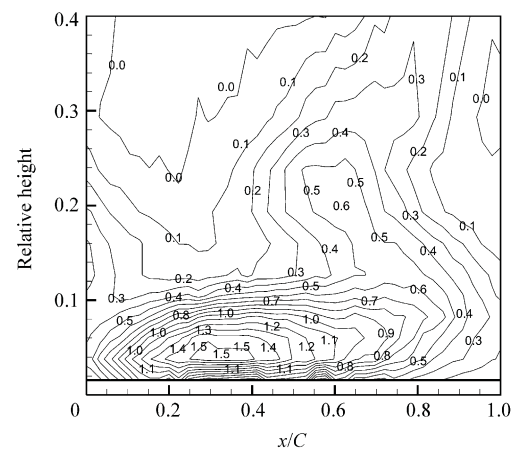


Fig.9 Total pressure loss coefficient contours with central blade 2.0% $H$  case and adjacent blade 3.0% $H$  case at  $Ma = 0.14$ .

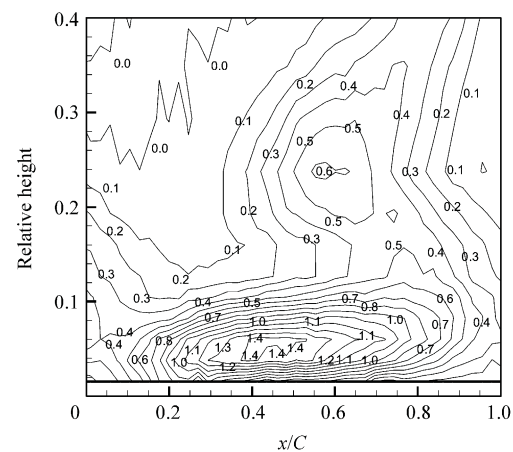


Fig.10 Total pressure loss coefficient contours with 2.0% $H$  case at  $Ma = 0.14$ .

### 3.4 Mass averaged tip clearance loss

The difference between the distribution of total

pressure loss measured in the cases with the tip clearance and the case without the tip clearance clearly reflects the effects of losses due to the tip clearance effects. Taking into account the mass averaged values, Fig.7 shows the total pressure loss coefficients caused by the tip clearance flow at the plane of 40% chord downstream of the cascade exit plane. It could be found that the mass averaged total pressure loss coefficients vary in approximate proportional to the tip clearance heights. In  $1.0\%H$  case, the total pressure loss coefficients at three exit Mach number are almost equal while in the cases with tip clearance heights of other than  $1.0\%H$ , the coefficient becomes higher as the exit Mach number increases. Ref.[9] showed that a growing tip clearance height would turn the total pressure loss caused by the tip clearance flow into a nonlinear fashion, although only three tip clearance heights were examined and the nonlinearity was indistinct. The results achieved in this paper again evidence the conclusion in Ref.[9] that, overall, the total pressure loss substantially rises with Reynolds number, but in the case of small tip clearance heights the total pressure loss is higher at lower Reynolds numbers. Compared with the effects of tip clearance height, the effects of Mach numbers and non-uniform tip clearance heights on the tip clearance flow are so small that they could be neglected.

#### 4 Conclusions

This paper presents detailed measurement and discussion on the tip clearance flow in the 40% chord downstream of the cascade exit plane of turbine cascade. It examines the effects of five different tip clearance heights, three different exit Mach numbers and non-uniform tip clearance height upon the tip clearance flow and has drawn the following conclusions:

(1) When the tip clearance heights in adjacent blades increase, the tip clearance flow across their tip gap strengthens, so it is with the pressure difference between the pressure side and suction side in the central passage. Moreover, the loss due to tip clearance flow on central blade increases.

(2) Under the experimental conditions of the study, generally, the total pressure loss proportionally rises with the tip clearance height. The results acquired in the study again evidence the conclusion in Ref.[9] that in  $1.0\%H$  case, the total pressure loss coefficients at different exit Mach numbers are almost equal while in the cases with tip clearance heights of other than  $1.0\%H$ , the coefficient becomes higher as the exit Mach number increases.

(3) Comparing with the effect of tip clearance height on tip clearance flow, the effects of exit Mach number and non-uniform tip clearance heights are so tiny that they could be neglected under the conditions of the experiments.

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